APPENDIX C BOUNDING EVENTS ANALYSIS

This preliminary bounding events analysis for the proposed Energy Systems Integration Facility (ESIF) at the National Renewable Energy Laboratory (NREL) has been developed using information available as of June 2008 (Manno 2008), supplemented by the draft ESIF Request for Proposal (RFP) (NREL 2009). The goal of this analysis is to identify the bounding events relating to life safety and property protection that could be used in the ~~draft~~ environmental assessment (EA) of the ESIF. Once established, these bounding events would represent the upper boundary of risk that would be presented by activities proposed for the facility. All other proposed and future work must have a level of risk below the bounding events, or a new assessment would be required to determine the significance of impact to the site. It is important to note that the ESIF bounding events analysis is necessarily an iterative process in the design/build delivery model; hence, the risk scenarios, hazards, controls, mitigations, and the risks themselves may change, evolve or be refined as the design progresses.

ESIF operations would require a number of materials, including nanomaterials, to be stored and processed at the facility. Some of these materials are hazardous. Data on the hazardous materials that would be present in the ESIF are based on the types of activities that would be performed in the various laboratories. Because the facility design process is in early stages, quantitative estimates of the amount of hazardous material present, as well as their physical state, are based on bounding estimates from design/build documents or based on experience operating similar processes in currently existing facilities. The majority of hazardous materials to be stored and processed at the ESIF are well understood. In addition, many facilities within NREL and throughout the world have used these hazardous materials safely.

> **Nanomaterials:** Nanoscale materials; materials with structural features (particle size or grain size, for example) of at least one dimension in the range 1 to 100 nanometers.
>
> **Nanometer:** One-billionth of a meter (10^{-9} meter).

The hazards posed by nanomaterials are less understood than more common hazardous materials, but for now NREL treats these materials as toxic and extremely hazardous, and uses controls commensurate with this assumed hazard. NREL would continue implementing this conservative approach until empirical-based evidence demonstrates that alternative precautions are effective. Although specific guidance on evaluation and control of the risks posed by nanomaterials is limited, preliminary research suggests that some of the controls used in conventional laboratory settings are effective and NREL has practical experience in the handling and control of these materials. In the case of the ESIF, the actual quantities of nanomaterials would be extremely limited because their use is not integral to most of the activities that would be conducted in the ESIF at this time; however, with the potential growth in this research area, NREL should consider laboratory designs for the ESIF that include engineering controls that are sufficient to protect workers, the public and the environment from nanomaterials.

The safety staff at NREL would apply their Hazard Identification and Control Procedure (NREL 2006) throughout the design/build process to ensure that the safety features incorporated into the facility would provide adequate protection to workers and the general public during facility construction and operations. In accordance with the Hazard Identification and Control Procedure, if, during the design process, the proposed safety features were shown to be inadequate, design changes or new safety features would be specified and shown to provide adequate protection. Before a laboratory would be used, the systems would be evaluated and readiness to operate them verified, in accordance with this procedure. Moreover, the Department of Energy, Golden Field Office, would provide independent oversight and verification reviews to ensure that NREL has met its commitments to identify, mitigate, and manage risk to an acceptable level.

The basis for the preliminary bounding events analysis is the risk matrix contained in Appendix A of the NREL Hazard Identification and Control Procedure (NREL 2006). The risk matrix is shown in Figure C-1.

Failure	Failure Frequency (per year)	Failure Consequence Severity			
		Catastrophic	Critical	Marginal	Negligible
Frequent	>1	High Risk	High Risk	Moderate Risk	Routine Risk
Reasonably Probable	1 to 0.1	High Risk	High Risk	Moderate Risk	Routine Risk
Occasional	$0.1 – 10^{-2}$	High Risk	Moderate Risk	Low Risk	Routine Risk
Remote	$10^{-2} – 10^{-4}$	Moderate Risk	Low Risk	Low Risk	Routine Risk
Extremely Remote	$10^{-4} – 10^{-6}$	Low Risk	Low Risk	Routine Risk	Routine Risk
Impossible	$< 10^{-6}$	Routine Risk	Routine Risk	Routine Risk	Routine Risk

Source: Appendix A of National Renewable Energy Laboratory Procedure No. 6-6.2, Hazard Identification and Control, 06/30/2006.

Figure C-1. Risk Assessment Matrix

In the Hazard Identification and Control Procedure, an event resulting in more than $1 million in equipment loss, death, or system loss is defined as Catastrophic. An event resulting in $100,000 to $1 million in equipment damage, severe injury or occupational illness, or minor system damage is defined as Critical. An event resulting in $10,000 to $100,000 in equipment damage, minor occupational injury or illness, or minor system damage is defined as Marginal. An event resulting in less than $10,000 in equipment damage, no injury or illness, or no system damage is classified as Negligible. Based on the Hazard Identification and Control Procedure, activities having Low Risk and Routine Risk are acceptable, and activities having High Risk or Moderate Risk levels must be approved by executive management on a case-by-case basis.

The NREL Hazard Identification and Control Procedure defines the scope of future hazards analysis reviews to be performed during facility design. The analysis contained herein relies on information available in the June version of the preliminary hazards assessment for the ESIF facility (Manno 2008), then supplements that assessment with information from the ESIF RFP (NREL 2009), to identify a series of events that could occur at the ESIF. Each event scenario is placed into a cell in the risk matrix based on the probability that the event would occur and the severity of the event. This process is performed twice for each event: once assuming that no protective features are in place, and a second time assuming that commonly used or already identified protective features are in place to prevent, protect, or mitigate that specific event.

Even though it is not possible to identify all possible events early in the design phase, the goal of this analysis is to consider many classes of events—for example, equipment failures, process upsets, and procedural errors as they are understood at this early stage of the design process. The objective of this exercise is to identify the representative and bounding events for the facility and the control sets that would be necessary to operate the facility within an acceptable level of risk. As design and construction proceed, consistent with the Hazard Identification and Control Procedure, more detailed hazards analyses would be performed so that changes in the facility hazards and design are adequately captured and analyzed. This would ensure that facility that workers, site workers, and the general public are adequately protected from any events that may occur after the ESIF becomes operational. As the design process proceeds, it is anticipated that some of the assumptions upon which this analysis is based would change. This may result in the identification of some new bounding events, others might be shown to be impossible, and still others might fall into a lower cell in the risk matrix. The identification of a new bounding event of higher significance would trigger a review of the impact of that event on the site.

This analysis is divided into four major sections. Section C.1 discusses major hazards and potential events based on the long history of hydrogen production and use around the world. The experiences presented in this section consider neither the likelihood nor the consequences of their occurrence at the ESIF. Section C.2 summarizes the risk tables developed as part of this bounding events analysis. Section C.3 quantifies some of the representative event scenarios identified in Section C.2. Section C.4 lists sources cited.

C.1 Hazards and Potential Events

Hydrogen

The generation, storage, and use of significant quantities of hydrogen at high pressures represents the major hazard at the proposed ESIF. The following discussion is a review of the more significant events associated with handling hydrogen at high pressures, and of their consequences, without considering the probability of their occurrence.[1]

The current design includes enough storage capacity for 250 kilograms of hydrogen. Storage pressures vary from 3,500 to 15,000 pounds per square inch (psi). The ESIF hazards analyses can build off the extensive National Aeronautics and Space Administration (NASA) experience handling large quantities of gaseous hydrogen at high pressures. Metals fabrication facilities also use large quantities of hydrogen, as does the petroleum refining industry. Overall, there have been many years of safe operation, as well as some spectacular failures. Clearly, the hazards of handling hydrogen are well-known, and there is every likelihood that it would be handled safely at the ESIF.

The hazards of handling hydrogen stem from its large flammability range—4 percent to 75 percent (Lees 2006, Table 16.4)—and its very low spark ignition energy—0.019 millijoules (mJ) (Lees 2006, Table 16.6). The Fire Protection Handbook (Cote 1986, p5-52) states: “Although its wide flammability range and high burning rate accentuate these hazards, its low ignition energy, low heat of combustion on a volume basis and its nonluminous (low thermal radiation level) flame exert counteracting influences in many instances.” The handbook (p 5-52) further states:

> Because of its low ignition energy, when gaseous hydrogen is released at high pressure, normally small heat producing sources, e.g. friction and static generation, often result in prompt ignitions. Accordingly, hydrogen is often thought of as self-igniting under these circumstances. A record of releases at high pressure reveals that fires rather than combustion explosions occur. When hydrogen is released at low pressure, self-ignition is unlikely and combustion explosions occur which are often characterized by very rapid pressure rises which are extremely difficult to vent effectively. Open air or space explosions have occurred from large releases of gaseous hydrogen.

The combustion explosions are often referred to as deflagrations. While some damage can result from the flame front, such as secondary ignition of combustible materials, most of the damage from a deflagration occurs from rapid pressure buildup from the heating of the reactants (hydrogen and oxygen), the combustion product water vapor, and the air. The pressure rise is limited by the extent to which the gases are confined. The pressure buildup is never greater than about 10 times the absolute pressure before

[1] The purpose of this document is to perform sufficient analyses to identify bounding accidents. Because hydrogen presents a significant hazard in the ESIF, much of the focus of the analysis has been on hydrogen accident scenarios. Consequently, this document should not be considered to be a comprehensive safety guide for the ESIF design.

ignition. While the peak pressure might be quite high, its duration is normally quite limited because of venting and the heat transfer between the hot gases and cold surfaces in the area where the fire occurred.

Because of its broad flammable range, if there is a leak of hydrogen in any area where hydrogen can accumulate, from a safety perspective it should be assumed that there would be a location where the hydrogen concentration is within the flammability range and that a spark source of sufficient energy to ignite the hydrogen would also be present. Given that it would be difficult to totally prevent leaks from occurring (the ESIF is, after all, a developmental facility), designs must take advantage of the rapid dissipation of released hydrogen. Specifically, the design must ensure that (1) released hydrogen cannot rise into an enclosed area, and (2) vent pipes designed to remove any hydrogen are not venting a flammable mixture of hydrogen and air. The metal fabrication industry places large holes in the roofs of its facilities, and the petroleum industry places much of its equipment outdoors to take advantage of the rapid diffusion and resultant dispersion of hydrogen gas to the atmosphere. Both of these design approaches avoid the difficult issue of ensuring adequate venting should a deflagration occur in a confined area.

It has been shown experimentally and theoretically that the flame front produced in an unconfined three-dimensional flammable gas cloud would not accelerate and produce a much more damaging explosive shock wave. That is not the case if the plume is confined in one or two of the three dimensions. Numerous detailed accident investigations have concluded that the damage resulting from partially confined plumes is much greater than would be expected for an unconfined vapor cloud deflagration. Similarly, if the flammable mixture is in a pipe of sufficient diameter (typically 1 inch or greater) and ignition occurs, the flame front rapidly accelerates; after about 10 pipe diameters, the flame front would reach sonic velocity and the resultant shock wave would split the pipe open.

Regarding the storage of hydrogen at high pressures, the failure of a vessel is judged to be in the Impossible range using the NREL risk matrix. A NASA-authored report discussing catastrophic storage vessel failure states: “Although there is a very low probability for catastrophic occurrence, selecting a site that would minimize the effects of such an event is prudent” (NASA 2004). The analysis then assumes a catastrophic failure of the pressure vessel and establishes a safe distance to the nearest building from the storage location. The basis for the distance comes from a modeling of the release plume. The objective is to place the storage location far enough away from any adjacent structure such that the release plume would be unconfined should it be ignited. National Fire Protection Association (NFPA) standards for hydrogen handling incorporate these distances.

High-pressure hydrogen would be stored in tube racks consisting of a number of cylinders, four to six, each about 20 feet long and 1 foot in diameter. Each cylinder is protected by a rupture disk, and all the cylinders in the tube rack are likely to be on a common manifold. The tube configuration is not unlike the tube trailers used to deliver high-pressure gases to facilities like NREL. Failure of a hydrogen storage cylinder is not anticipated. If a cylinder did fail, it would not be expected to cause an adjacent pressure cylinder to fail because such vessels are often made of ductile metals.

Under this failure scenario, one of the pressure cylinders fails and generates a large gas cloud. While such failures are rare, those that have occurred are often the result of hydrogen embrittlement in an area sensitized following welding. Accumulation of combustibles, trash, or a fuel spill around the pressure cylinders could also result in cylinder failures if a fire occurred. The 20-foot-long storage vessels are long enough to make it possible for a fire to overheat one end of a vessel; if the rupture disk is at the other end, the vessel could fail catastrophically before it vented to the atmosphere. Even in this case, although several vessels might be close to failing, it is not expected that they would fail simultaneously. Based on information supplemental to the bid package provided by NREL, the maximum quantity in one vessel, 25 kilograms, limits the energy that would be released should one or more of the storage vessels fail.

Another hydrogen hazard that must be considered is the quantity of hydrogen that could be released should a high-pressure hydrogen pipe be damaged and fail. The system would be provided with a quick-acting isolation valve that would isolate the hydrogen in the line from the storage vessels when the pressure in the piping drops rapidly. Often, the volume of hydrogen that exits the system before shutdown is initiated and the volume that exits after shutdown is great enough to cause all or a large portion of the atmosphere in a laboratory room to exceed the lower flammability limit for hydrogen in just a few seconds. An ignition source, if present, would ignite the gas cloud, and because the cloud is confined, the pressure in the room would rapidly rise. If the whole room were in the flammable range at the time of ignition, the pressure would breach the walls and potentially damage adjacent laboratories. As previously discussed, if the vented hydrogen accumulates in a pipe and the flammable mixture ignites, an even more damaging detonation could occur.

There are other properties of hydrogen that present some hazards. Explosions have occurred within a pressure cylinder if air is not purged from the cylinder before hydrogen is added. Static electricity could ignite the hydrogen concentration if within the flammability range. The flame front formed would accelerate down the cylinder and detonate. Such a detonation would be violent enough to cause the remaining cylinders to fail. This risk is documented.[2]

Another hazard of hydrogen is associated with its interaction with the pressure cylinder. If the hydrogen is extremely pure, which might be the case with hydrogen generated on-site, the pressure vessel would be more susceptible to hydrogen embrittlement.

General Controls used for Hydrogen. Hazard controls for hydrogen use and other safety precepts applied to hydrogen systems generally include the following:

- Providing adequate ventilation, as well as designing and operating hydrogen systems to prevent leakage, and eliminating potential ignition sources.
- Installing barriers or safeguards to minimize risks and control failures.
- Installing safety systems to detect and counteract or control the possible effects of such hazards as vessel failures, leaks and spills, embrittlement, collisions during transportation, ignitions, fires and explosions, cloud dispersions, and the exposure of personnel to flame temperatures.
- Maintaining a safe interface under normal and emergency conditions so at least two failures occur before hazardous events could lead to personal injury, loss of life, or equipment or property damage.
- Installing warning systems to detect abnormal conditions, measure malfunctions, and indicate incipient failures. Providing warning system data transmissions with visible and audible signals that have sufficient redundancy to prevent any single-point failure from disabling the warning system.

[2] See: "Assessment of detonation hazards in high-pressure hydrogen storage from chemical sensitivity analysis," online at http://cat.inist.fr/?aModele=afficheN&cpsidt=18471100.

- Installing safety valving and flow regulation that would adequately respond and protect personnel and equipment during hydrogen storage, handling, and use.
- Using automated control systems with caution and warning feedback inputs. Also, constraining manual controls within the systems by using automatic limiting devices to prevent over-ranging.
- Applying a system of verifications of equipment, power, and other system services for safe performance in the design and normal operational regimes.
- Applying "fail-safe" system design, meaning that any single point failure from which potentially hazardous conditions are a risk must cause the system to revert to conditions that would be safest for personnel and with the lowest property damage potential.
- Applying redundant safety features to prevent a hazardous condition when a component fails.
- Subjecting all plans, designs, and operations associated with hydrogen use to an independent, safety review. Safety reviews should be conducted on effects of fluid properties, training, escape and rescue, fire detection, and fire fighting.
- Establishing operating procedures for normal and emergency conditions and reviewing these procedures as appropriate.
- Performing hazards analyses to identify conditions that may cause injury, death, or property damage.
- Assuring continuous improvement of systems through reporting, investigating, and documenting the occurrences, causes, and corrective actions required for mishaps, incidents, test failures, and mission failures in accordance with standardized procedures.

All of these safety controls and precepts are currently used at NREL and NREL's Integrated Safety Management System provides a rigorous administrative structure and requires resources to ensure that these safety precepts are successfully applied to the ESIF.

Natural Gas

In addition to the hazards of handling hydrogen gas in the ESIF, other hazardous materials would also be used in the facility. Natural gas presents some of the same flammability and explosive hazards as hydrogen; however, the flammability range of natural gas in air is narrower, mainly at the high end—the lower flammability limit is 5 percent and the upper limit is 15 percent. The confined-space deflagrations associated with natural gas are just as severe when they occur. For this analysis, the assessments are bounded by the hydrogen scenarios being considered.

Toxic Gases

The facility would contain limited quantities of toxic gases, such as hydrogen sulfide, whose release could pose a risk to workers' health should it occur. Based on discussions with safety personnel at NREL, any hydrogen sulfide contained in high-pressure gas cylinders would be diluted with a carrier gas such as argon or nitrogen, such that any accidental discharge is unlikely to exceed any exposure limits. It was stated that the concentration of the hydrogen sulfide in the gas cylinders would not exceed 40 parts per million (ppm) and the Emergency Response Planning Guideline (ERPG)-2 limit of 30 ppm. The turbulent jet caused by a release would be expected to induce enough mixing with the surrounding air to limit the volume above 30 ppm to a very small volume. These releases are not considered to be bounding accidents.

Nanomaterials

Limited quantities of nanoparticles may be used in the ESIF. It is expected that fewer than 10 grams of nanomaterials would be present at any location; these materials are, in most cases, immobilized on a solid substrate.[3] Because the hazards of these materials are not completely understood, NREL would follow its Chemical Safety Procedure, which incorporates DOE and National Institute of Health and Human Services (NIOSH) guidelines on nanomaterials. Based on these guidelines, the naonparticles would be handled in inerted gloveboxes or ventilated enclosures with HEPA filtration and would be transported, if necessary, in properly sealed containers within secondary containment.

In general, if a material presents a hazard as a particulate, it is commonly assumed that the hazard would also be realized and perhaps enhanced if present as nanoparticles. For example, fine carbon particles dispersed in air present a dust explosion hazard. The same hazard is likely present for carbon nanoparticles dispersed in air. The risk could be higher for nanoparticles because if they became charged with static electricity, nanoparticles would readily disperse and, being lighter, would presumably be easier to entrain in the air. Both phenomena would make the nanoparticles more likely to generate a dust cloud explosion, which would be limited in effect because of the small quantities in use. Alternatively, if nanoparticles are immobilized on a solid substrate or in a form that tends to clump together (often observed), the hazard would be no different than that posed by larger particulates. Following the NIOSH guidelines, this material would be handled in inerted gloveboxes and, if present in dispersible form, would be transported, if necessary, in closed cans with taped lids.

Spills and Other Hazards

Spills of diesel and gasoline pose a lesser threat but are sufficiently different from a gas release to be considered separately.

There is a small risk from spills of acids and caustic materials that mainly present a risk to workers; such risks could be largely controlled by having workers don protective equipment (such as gloves and face shields) and performing the work in a hood or other type of enclosure. Furthermore, whenever multiple chemicals are present in a facility, there is a risk of incompatible reactions; however, based on the list of chemicals that could be present in the ESIF, the risk of incompatible chemicals mixing and causing a violent reaction appears to be low.

Because the ESIF would deal with full-sized equipment that would be prototypic of equipment to be used on an industrial scale, the risk of over-pressurization and subsequent failure would be present. Such failures are largely a risk to workers; however, they can also cause damage to adjacent equipment when they occur.

Finally, there are risks associated with stored energy sources, which includes electrical energy and compressed gas. The ESIF would develop systems to manage high-voltage and high-amperage electrical circuits. More common industrial hazards, such as high-pressure gas cylinders, present a significant source of stored energy should a valve be sheared off during handling.

[3] Information based on NREL e-mail transmittal.

Natural Phenomena

The natural phenomena risk was not addressed in this bounding events analysis. It is assumed that any accidents resulting from natural phenomena, should they occur, would be bounded by the accidents considered in this appendix. For example, a pipe break that might occur as a result of a faulty weld could occur in an earthquake from equipment movement.

Summary

Overall, the vast majority of the potential ESIF hazards are known and are well-understood. Section C.2 presents a more detailed analysis for several accidents that are believed to be the bounding events for the ESIF. Some effort was made to identify a location where these bounding events might occur. In general, any location mentioned is considered to be representative of analogous areas. In any future detailed safety assessment, the adequacy of safety features for every process that could result in the accidents described in Section C.2 would have to be assessed.

Even though many of the laboratory operations proposed for the ESIF are currently being performed at NREL, the scale of these activities would increase in some cases, and the integration and potential co-location of these operations in one facility pose challenges for the design-build team. Given the nature of design-build projects and the design challenges of this facility, it is important that the design-build team perform rigorous process hazard analyses.

C.2 Bounding Events Analysis

Section C.1 discussed many of the hazards that could be present in the ESIF. This section attempts to list some accident scenarios where these hazards might be realized during ESIF operations. The goal of the bounding events analysis is to identify a sufficient number of plausible event scenarios from the many classes of events, external accidents, equipment failures, procedural errors, etc., to identify the bounding events for the ESIF.

Section 5 of the RFP, which provides an inventory of equipment and energy sources for the proposed ESIF, was used as a starting point to determine plausible events for each of the listed laboratories. Most of the safety features specified were identified in the June 2008 preliminary hazards assessment (Manno 2008). For the new laboratories not addressed in the June 2008 assessment, the safety features were applied based either on the safety features listed for similar laboratories or on known standards discussed in Section C.1. Additional hazards analyses must be performed as the design progresses and safety features that are judged to be more effective would replace or supplement the features listed in this report.

The risk matrix is used to select a few bounding events for more detailed analysis in Section C.3; however, one other criterion has also been applied. When discussing hydrogen storage, NASA analyzes the catastrophic failure of a storage vessel even though such an event falls in the “Impossible” probability range on the NREL risk matrix. NASA states that such assessments are prudent given the potentially severe consequences.

C.2.1 Methodology

In performing this preliminary bounding events analysis for the ESIF, each event determined to be plausible is placed in one of the NREL risk matrix bins (see Figure C-1). This process is performed twice: once assuming no safety features are in place, and a second time imposing safety features identified in pertinent standards (Section C.1) or listed in the June 2008 preliminary hazards assessment (Manno 2008). By performing the analysis twice, both the importance and effectiveness of the safety features can be shown. Those events judged to bound the event sequences with the safety features present are candidates for more detailed analysis. The analysis lists the key assumptions, followed by a summary of the representative scenarios listed in Addendum 1 of this appendix.

It is possible to estimate the likelihood of initiating events by applying some general estimating techniques that are frequently used when initiating a hazards assessment of a proposed facility. Such estimates consider three classes of events: the failure of static systems, the failure of active systems, and failures initiated by human error. The failure rate of static components is often in the range of 10^{-3} to 10^{-6} per year. Well-maintained active systems frequently fail at a rate of between 10^{-2} to 10^{-4} per year, and human-caused initiating events are often in the 10^{-1} to 10^{-3} range. The latter depends on the number of times the procedure has to be repeated per year. If it is anticipated that an activity would be performed hundreds of times each year, an estimate at the high end of the range is used. If the activity would be performed only occasionally, a number at the lower end of the range is used. This technique is used in this bounding events analysis to bin the event sequences with no safety features present.

The next step is to expand the analysis by binning the same events with the safety features present and applying roughly the same failure probability ranges for the ineffectiveness of static and active safety systems and administrative controls designed to reduce human error. The use of multiple safety features does not necessarily increase the effectiveness of the systems significantly because of common-cause failures. Because the design for the ESIF has yet to be specified in detail, the frequency of initiating events is typically assigned a value toward the high end of the failure range given above. For hydrogen systems, since the safety systems are well-developed, values closer to the lower end of the failure range are used for the ineffectiveness of the safety systems incorporated. After the second binning of the event sequences, the bounding events are identified.

This analysis technique may seem coarse, but it is appropriate for an initial assessment when little or no design information is available. It is often possible to identify those major events that are catastrophic and frequent in the absence of safety features and remain high in the risk matrix after the safety features have been taken into account. A catastrophic and frequent event scenario without safety features often remains high on the risk matrix after the safety features have been applied when it is necessary to rely heavily on administrative controls instead of on the more effective active or passive safety features. These event scenarios typically become the bounding events.

C.2.2 Key Assumptions

1. This preliminary bounding events analysis is based on the inventory of equipment and energy sources as shown in Section 5 of the draft RFP for the design and construction of the ESIF (NREL 2009). If additional operations, equipment, and chemicals are incorporated into the design, the analysis must be updated to meaningfully reflect the facility risk level and the related safety envelope.

2. The intent of this analysis it to provide a reasonable upper bound on the risk levels associated with ESIF operations. This analysis does not meet the requirements identified for a preliminary hazards analysis review specified in NREL’s Hazard Identification and Control Procedure (NREL 2006) because of its limited focus. When identifying bounding events, it is necessary to identify all the classes of events that might occur and, from those events, select the bounding events.

3. As additional design details become available, it would not be necessary to modify documents that use this analysis as long as a documented risk assessment is conducted showing that the event

scenarios that define the facility risk level and the related safety envelope as defined in this appendix remain bounding.

4. This preliminary bounding events analysis shows two risk levels: one without operational safety features and one with operational safety features. The second would be used when estimating facility impacts. The first, although it is stated to be evaluated without safety features present, was evaluated with common industrial safety systems incorporated in the design and operation. For example, it was assumed that a hydrogen storage vessel is designed to withstand its normal operating pressure and to use proper construction materials. Otherwise, the frequency of a vessel explosion and all the other events identified would be Frequent. The likelihood of an explosion without the safety features operational was estimated by removing the listed safety features.

5. Without knowledge of the design of each safety system, only ranges of effectiveness can be estimated. In general, safety systems that rely on procedural controls—for example, a trained operator monitoring gauges—would reduce the probability of an event by factors of 10 to 100. Active safety systems would reduce the probability of an event by factors of 100 to 1,000, and passive safety systems by factors of 100 to 10,000. For this analysis, it was assumed that little reliance would be placed solely on procedural controls, while recognizing that even active and passive safety systems rely on effective inspection and maintenance procedures.

6. The goal of this analysis is not to provide a worst-case analysis; rather, it is to identify the bounding events. Expected values have been used when evaluating scenarios.

7. To identify bounding events, it is not necessary to generate a probabilistic risk assessment. Performing a probabilistic risk assessment requires a complete design; all written operating, inspection, and maintenance procedures; and ideally some facility operational experience. This preliminary analysis uses ranges of values for event rates and consequence levels to screen events and, from the screening process, identify those scenarios that are most limiting. The frequency of their occurrence and the magnitude of the potential consequences have been estimated using historical failure data and safety system reliability data. In the second part of this analysis, an effort is made for each bounding event to quantify the magnitude of its potential impacts. Because the design has yet to specify the safety equipment (including specific types of safety equipment), conservative estimates have been used.

C.3 Representative Event Scenarios

The first step in identifying a set of representative event scenarios is to plot the risk level for the scenarios shown in Addendum 1.[4] Figure C-2 places each event sequence listed in Addendum 1 in a bin on the risk matrix assuming that no safety features have been installed to protect against the hazardous materials present in the laboratories. Figure C-3 places each event sequence in a bin in the risk matrix assuming that safety features have been installed in the laboratories. A comparison of the two tables shows that safety features are critical and that effective safety features can ensure the safety of workers and the general public.

[4] Because the information associated with each event scenario in Addendum 1 is sometimes incomplete, the notation "AI" is used in the addendum to identify action items. These items, when addressed, would enable the scenario to be better defined, with the result that the risk level could be assigned with greater accuracy.

Annual Frequency	Severity Level			
	Catastrophic	Critical	Marginal	Negligible
Frequent	ESL-1, HPTF-4	OTP-7		
Reasonably Probable	HBML-8, HVHC-1, PEL-2, HPL-1, HPL-2, HPL-6, HPL-7, OTP-1, OTP-4, OTP-5, FQL-7	HVHC-3, SGC-1, HPL-3, OTP-2, ESL-2, TP-2, TP-3, AM-4, AM-5, FCL-3, FQL-2, FQL-3	HBML-1, HBML-3, ESL-3, ML-1, AM-1, AM-3, FQL-5	
Occasional	HBML-5, OTP-6, SL-1, FCL-1, FQL-4, FQL-8	AB-1, HBML-2, HBML-4, HBML-6, HBML-7, HVHC-2, AM-6, FCL-2, FQL-1, FQL-6	AM-2	
Remote	HBTC-3, OTP-8, OTP-9, MS-2, OTB-1	AB-2, HBTC-1, HBTC-2, HBTC-4, SHOT-1, HPL-4, HPL-5, OTP-3, HPTF-1, HPTF-2	ML-2	
Extremely Remote				
Impossible				

Note: White cells = high risk Turquoise cells = low risk
Tan cells = moderate risk Yellow cells = routine risk

Figure C-2. Risk Profile for Events without Safety Features

Annual Frequency	Severity Level			
	Catastrophic	Critical	Marginal	Negligible
Frequent				HPTF-4
Reasonably Probable				HVHC-1
Occasional			HBML-5	
Remote		OTP-9	HBML-3, HVHC-2, SGC-1, HPL-5, HPL-7, OTP-7, AM-4, AM-5, FQL-5	AB-1, HBML-1, HVHC-3, HPL-3, OTP-4, OTP-5, TP-2, TP-3, ML-1, AM-1, AM-3
Extremely Remote	OTP-8, FQL-7	HPL-4, OTP-2, SL-1, SL-2, HPTF-2, AM-6, FQL-3, FQL-8	HBML-2, HBTC-3, HPL-2, OTP-1, OTP-3, OTP-6, MS-2, TS-1, TP-1, OTP-1, FQL-1	AB-2, HBML-7, HBTC-2, HBTC-4, HPL-1, HPL-6, ESL-1, ESL-2, ESL-3, ML-2, FCL-1, FCL-2, FCL-3, FQL-2, FQL-4, PEL-2
Impossible			HBTC-1, SHOT-1	HBML-4, HBML-6, HBML-8, AM-2, FQL-6

Note: White cells = high risk Turquoise cells = low risk
Tan cells = moderate risk Yellow cells = routine risk

Figure C-3. Risk Profile for Events with Safety Features

In comparing Figures C-2 and C-3, it is evident that preventive, protective, and mitigative safety features significantly lower the risk profile for the ESIF. Figure C-2 shows that in the absence of safety features, many event scenarios are high-risk (high frequencies with severe consequences). With safety features in place (Figure C-3), none of the scenarios are high-risk. The most frequent events with the highest severity consequences, and the events that lie along the spectrum between the two, define the facility's safety envelope.

The following events provide some definition on the safety envelope for the ESIF (see Figure C-3). As the programming and design become more complete, the safety envelope would be revised and refined.

- One extremely remote probability event with catastrophic consequences: the rupture of a hydrogen supply line within a laboratory as mentioned in FQL-7 (this scenario is judged to be extremely remote and catastrophic). HBML-5 is a similar event, estimated to have an occasional probability and marginal consequences.
- One extremely remote probability event with catastrophic consequences: the detonation of a hydrogen storage vessel as it is being filled (OTP-8).
- One remote probability event with critical consequences: the failure of a research component on an outside test pad (OTP-9).

Numerous additional event sequences are less limiting because they have a lower frequency of occurrence or a lower severity level (or both). There are also some events, such as the catastrophic failure of a pressure storage tube, that are prudent to analyze even though they did not rise to the level of a bounding event. Given the uncertainty in the design, nonbounding events should not be totally dismissed because their probability of occurrence, the effectiveness of safety systems, or the consequences of the event might have been over- or underestimated. For this reason, Section C.3.1, where several events are quantified, considers several classes of events.

Figure C-3 shows two similar event scenarios all associated with the deflagration of an enclosure following a breach of a hydrogen line: FQL-7 and HBML-5. These two scenarios point out one of the difficult design issues the ESIF faces. There would be thousands of feet of high-pressure hydrogen tubing in the facility; some equipment (such as a 1-MW generator set) would be quite large, which means that the tubing must be able to provide many grams per second of hydrogen to the test device. This would require large flows at relatively small pressure drops, making a leak that does not trigger the isolation valves a possible limiting design consideration.

The detonation of a hydrogen storage cylinder as it is being filled is a limiting accident. It was noted in Section C.1 that individuals often think of high-pressure hydrogen as being spontaneously combustible when it is discharged; in fact, if the air were not evacuated from a storage cylinder and high-pressure hydrogen were used to fill it, this exact circumstance is produced. Such a detonation has the potential to fail other storage cylinders, which, if they were filled with hydrogen, would add to the consequences. The accident is prevented not by design but by following procedures. Such transient scenarios point out the importance of looking at the off-normal, not the normal, conditions at a facility.

Another event, the failure of a storage vessel containing hydrogen at several thousand pounds per square inch, has a low probability of occurrence and as a result is not categorized as a bounding event but nevertheless should be analyzed as such. NFPA Standard 55 (NFPA 2005) specifies an exclusion zone of 50 feet. Within this zone, the following restrictions apply:

- There should be no other buildings.
- There should be no flammable storage tanks or combustible materials.
- The hydrogen tanks should not be in a trench.
- If liquid combustible storage is located in the vicinity, the hydrogen tanks must be above the level of the combustible storage tanks. This configuration ensures that there is no possibility that a discharge of the combustible material would collect under the hydrogen storage cylinders.

It is assumed that these safety requirements would be met for the hydrogen storage units for the ESIF.

A number of Extremely Remote event scenarios are estimated to have Critical consequences (see Figure C-3). These include failures of outside hydrogen compressors, leaks that result in the buildup of explosive gas concentrations in confined spaces, and drops of pressurized gas cylinders. The frequency of the latter class of events (drops of pressurized gas cylinders) is driven by human error; therefore, it is premature to lower to Impossible at this time. One additional event from these lower risk bins would also be analyzed: the shearing off of the valve on a pressurized gas cylinder.

In an effort to identify various classes of events, it is clear from Figure C-3 that workers could be exposed to toxic gases; that flammable gas clouds could form and, if ignited, could result in catastrophic damage to the laboratory and to adjacent laboratories; that high-pressure equipment could rupture; and that workers could be exposed to the unknown risks from nanomaterials. Thus, to complete the list of representative events to be analyzed in greater detail, one of each of the above classes of events is analyzed in greater detail in Section C.3.1.

C.3.1 Analyses of Representative Event Scenarios

Based on the above discussions, four event scenarios have been selected for detailed analysis: a compressor failure, the rupture of a hydrogen storage vessel, the shearing off of a valve on a pressure cylinder, and the leakage of hydrogen into a confined space resulting in deflagration. A fifth scenario, a spill of nanomaterials, is also included, but because of uncertainties in estimating the consequences of such a spill, this event is discussed in less detail.

1. Compressor Failure

It is assumed that the compressor has a volume of 1 liter and is operating at a pressure of 15,000 psi. The energy generated by the failure can be estimated using the equation (Lees 2006, Equation 17.4.28, page 17/26):

$$E = \frac{pV}{\gamma - 1} \qquad \textbf{Eq. 1}$$

where E is the energy generated
P is the pressure (units of Pa)
V is the volume (units of m^3),
γ is the heat capacity ratio (C_p/C_v), which equals 1.4 for a diatomic gas such as hydrogen or for dry air.

The key assumption is the free volume inside the compressor. The energy released from the compressor failure is 0.26 megajoules (MJ), or the equivalent of 55 grams of trinitrotoluene (TNT). The energy of the pressure pulse from this event would be equivalent to about 22 grams of TNT and would cause damage for a few tens of meters. The biggest threat would be from the potential shrapnel produced. More details regarding the mass and internal volume of the compressor are needed to quantify the extent of the impact.

The arrangement of the compressor relative to other equipment and the presence of any barriers could also significantly affect the extent of impacts. Overall, if the volumes are correct, this is a relatively small explosion which could be effectively limited. The greater concern would be the shrapnel generated from the explosion. Note that if the internal volume in the compressor is significantly greater than 1 liter, an estimated value, then the failure would cause proportionately greater impacts.

2. Hydrogen Storage Vessel Rupture

The same equation used for the compressor failure analysis is valid for the storage vessel rupture. The volume of the vessel needed to store 25 kilograms of hydrogen at 15,000 psi is approximately 0.3 cubic meters. Using Eq. 1, the energy released is equivalent to about 15 kilograms of TNT. The energy of the pressure pulse from this event would be equivalent to about 6 kilograms of TNT. A diagram of the proposed tube trailer shows five storage cylinders; if one catastrophically failed, the others are strong enough to withstand the failure. As previously mentioned, the presence of safety features reduces the probability that this event would occur from Extremely Remote to Impossible, using the NREL risk matrix. The estimated severity remains Catastrophic. Based on Figure 17.98 in Lees (2006, page 17/205), shrapnel from this explosion could be ejected up to a quarter of a mile from the facility. The Lees scenario assumes a cased explosive, which is typically very thin-walled. No shrapnel from a pressure vessel failure at the ESIF would be expected to travel that far. Thus, the real danger is to people close to the tube trailers, which is one reason for excluding all but essential personnel from the vicinity of the tube trailers.

If one of the tubes in a tube trailer filled and if all were piped together, all the hydrogen would be released. NFPA 52 specifies a minimum separation distance of 20 feet for gas storage (NFPA 2006). A release from a hydrogen tube trailer occurred in Stockholm, Sweden, in 1983 on a city street lined with buildings several stories high, and the consequences were devastating. Clearly, the deflagration was confined (Venetsanos 2003). More analysis is needed to ensure that no off-site impacts would result from such a catastrophic event. NREL is committed to requiring the design-build team to perform such analyses selecting final sites for all the hydrogen storage vessels that are being proposed to support ESIF activities.

For an explosion equivalent to 6 kilograms of TNT, the overpressure at 30 meters is estimated to be slightly over 2 psi. At this overpressure, a nonreinforced cinderblock wall could be shattered (Lees 2006, Table 17.42). Glass would be broken, and personnel exposed to the flying glass could be injured. At 30 meters, using the most conservative model for eardrum injury, 1 percent of the exposed individuals might experience eardrum rupture (Lees 2006, p. 17/237). The overpressure is not sufficient to cause lung damage or produce fatal injuries. Shrapnel striking a person could produce fatal injuries.

3. Shearing off a Valve on a Pressure Cylinder

Based on information from Linde (2004), a #1 steel cylinder has a tare weight of 136 pounds and a capacity of 1.72 cubic feet and is commonly filled to a pressure of 2,400 pounds per square inch gauge (psig); this is considered a representative gas cylinder. If it were filled to a higher pressure or contained a higher molecular weight gas, the cylinder would be accelerated to a higher velocity before its contents were spent. A lighter gas bottle would also be accelerated to a higher velocity if it contained the same quantity of gas. At the same molecular weight, a monoatomic gas would also accelerate the cylinder to a higher velocity, in proportion to the square root of the heat capacity ratio.

Given the above parameter values, and assuming the sheared-off pipe section is ¾-inch schedule 80 pipe, the final velocity of the pressure cylinder is 50 meters per second, or approximately 110 miles per hour.

The analysis shows that although the results may vary, gas storage cylinders have the potential to attain high velocities. If a worker were struck with a cylinder weighing almost 140 pounds at 100 miles per hour, serious injuries could occur. Smaller lecture-sized bottles would not be capable of doing as much damage, but they could nevertheless strike a person at a significant velocity and cause injury.

At NREL, high-pressure gas cylinders are used in many laboratories, and the procedures for safe handling are well-developed. Furthermore, training ensures compliance with the procedures. Thus, while the consequences of such an event could be catastrophic in terms of equipment damage or worker injury, the safe handling practices employed at NREL reduce the frequency of this event to the Impossible probability range in the NREL risk matrix. The analysis shows the importance of complying with NREL procedures for the safe handling of gas cylinders.

4. Leakage of Hydrogen into a Confined Space

For purposes of this analysis, it is assumed that a 0.25-inch outside diameter high-pressure hydrogen tube containing 150 psig hydrogen is breached. Assuming that the tubing is rated for 20,000 psi, the inside diameter is 0.109 inch. Again, for purposes of this analysis, the supply pressure is 150 psig, the length of tubing from the reduction valve to the point of the leak is 100 feet, and the pressure drop caused by the leak is 50 psig. This pressure drop was assumed to not cause the quick-acting excess-flow valve to shut, so the system would continue to operate. Because the hydrogen flow through the tubing is compressible, a computational fluid dynamics code was run to estimate the discharge rate from the tubing; the result was 0.213 grams of hydrogen per second. Once that lower explosive limit is reached, a deflagration of the chamber is possible.

Many other similar calculations could have been performed using different laboratories. Some have much larger pressures and some have much greater flow requirements, probably indicating that for some facilities, a 3/8-inch outside-diameter tube with an inside diameter of 0.206 inch might be required just to supply the required hydrogen. For that outside diameter, 100 feet of tubing at 50-psig pressure drop can discharge 1.14 grams per second of hydrogen—still not enough for a 1-megawatt electrical (MWe) generator requiring tens of grams of hydrogen per second.

The design of the ESIF has not been specified to this level of detail, so these calculations are all hypothetical. They show that the potential exists for hydrogen to build up in chambers to concentrations above the lower flammability limit quite quickly. Thus, this type of accident is expected to continue to be a bounding accident that must be addressed throughout the design and operations.

5. Spill of Nanomaterials

The U.S. Department of Health and Human Services has developed a report titled *Approaches to Safe Nanotechnology* (NIOSH 2009). This document points out the great uncertainty in estimating the consequences should a person be exposed to nanomaterials. Given the lack of good impact estimates, it must be assumed that a spill of nanomaterials during transfer could result in serious long-term health effects to any individual who came in contact with or inhaled the particles.

The NIOSH report states that the properties of nanomaterials are often different from those of other materials having the same composition; as a result, nanomaterials could present an increased handling risk. For example, nanomaterials could pose a major static electricity hazard. If a dust cloud of nanomaterials formed and were ignited, the explosion could breach any enclosure. The resulting debris from the failure of the enclosure would pose a risk to workers. Safety features might include inerting the gloveboxes until it can be shown that the nanomaterials pose no risk from static electricity initiation or from the ignition of a dust cloud of nanomaterials.

C.3.2 Summary and Conclusions

This bounding events analysis has identified many possible events that could occur at the ESIF and has analyzed in detail several of the more severe event sequences. The analysis concludes that several events have the potential for significant impacts to site workers and possibly the general public and emphasizes the importance of incorporating effective safety features into the design. This analysis shows there is ample justification for using formal hazards analyses, as specified in the NREL Hazard Identification and Control Procedure, to guide the design process as it proceeds.

The calculations in this analysis are preliminary and limited. The ESIF would be a complex facility with thousands of feet of piping and numerous safety devices of varying types that must function with high reliability to ensure safety. All results depend on material quantities and the conditions under which ESIF materials would be handled. As the design is derived and refined, these bounding events would become more refined and more precise calculations can be performed.

Despite the limitations of the analyses as stated above, it can also be said that except for nanomaterials, decades of experience safely handling these materials have resulted in the development of a highly reliable suite of adequate preventive, protective, and mitigative safety features to ensure that a well-designed ESIF can be operated safely. Any finding of no significant impact must be based on the assurance that comprehensive safety assessments would be successfully completed during the design phase of the ESIF. The design-build team would need to perform rigorous process hazard analyses to define the hazards and operability envelope for the ESIF.

Regarding the handling of nanomaterials, given the lack of NIOSH exposure limits, DOE and NIOSH guidance for the safe handling of these materials must be incorporated into the design and ESIF operating procedures.

C.4 References

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Addendum 1
Event Scenarios[a]

Scenario Number	Laboratory/ Energy Source	Hazard(s)	Quantity	Likelihood of Occurrence (Without Safety Features)	Severity (Without Safety Features)	Possible Preventive/ Protective/ Mitigative Measures	Likelihood of Occurrence (With Safety Features)	Severity (With Safety Features)	Risk Level (Without Safety Features/ With Safety Features) Comments
Energy Analysis GIS Laboratory									
GISL-1	Electricity	Standard industrial hazard							
Materials and Computational Sciences Center (MCSC) High Performance Computer Data Center									
HPC-1	Fire from electrical short in cable tray	Standard industrial hazard							
Applied Battery and Electronics Laboratory House nitrogen, 6 – gas cylinders, (oxygen, argon, forming gas (hydrogen-nitrogen mix), powdered lithium									
AB-1	Oxygen gas	Fire accelerant	Oxygen leak	Occasional	Critical: Oxygen-enhanced fire consumes equipment and materials such as lithium in gloveboxes	Standard operating procedures, noncombustible materials of construction, ventilation	Remote	Negligible: Materials of construction would limit spread of fire, ventilation the concentration buildup	Moderate Risk / Routine Risk

Event Scenarios[a]

Scenario Number	Laboratory/ Energy Source	Hazard(s)	Quantity	Likelihood of Occurrence	Severity	Possible Preventive/ Protective/ Mitigative Measures	Likelihood of Occurrence	Severity	Risk Level (Without Safety Features/ With Safety Features) Comments
				Without Safety Features			With Safety Features		
AB-2	Lithium powder	Alkali metal fire	Lithium fire	Remote	Critical: Metal fire could damage equipment and produce toxic smoke	Inerted glovebox to contain lithium in a finely divided state. metal fire extinguishers close to where lithium is being used or stored	Extremely Remote	Negligible: Inerting of glovebox eliminates risk of a metal fire, Class D fire extinguishers	Low Risk / Routine Risk
Center for Electricity, Resources and Building Systems (CERBS) High Bay - Main Laboratory 1-MW Grid Simulator (High-Voltage High-Current), Research Fuel Lines (diesel, biodiesel, natural gas, and hydrogen lines), corrosives and flammables									
HBML-1	Solvents	Small local fire in work area	Assume liter- to gallon-sized, non-breakable containers	Reasonably Probable	Marginal: Injury to a worker (burns); possible loss of equipment	Low combustible loading, solvents used in fume hood	Remote	Negligible: Minimal equipment damage, minor worker injury	Moderate Risk / Routine Risk
HBML-2	Solvents	Room fire	Assume many liter- to gallon-sized bottles in storage cabinets	Occasional	Critical: Room fire that damages equipment and life-threatening worker injury from burns and toxic smoke exposure (from involvement of corrosives)	Nonflammable storage cabinets, flammable-gas monitors, fire suppression equipment, activities with flammables performed in fume hoods	Extremely Remote	Marginal: Fire that is confined to a small portion of the room and is extinguished before much damage to equipment occurs	Moderate Risk / Routine Risk

Event Scenarios[a]

Scenario Number	Laboratory/ Energy Source	Hazard(s)	Quantity	Likelihood of Occurrence (Without Safety Features)	Severity (Without Safety Features)	Possible Preventive/ Protective/ Mitigative Measures	Likelihood of Occurrence (With Safety Features)	Severity (With Safety Features)	Risk Level (Without Safety Features/ With Safety Features) Comments
HBML-3	Corrosives	Small spill of corrosives in work area	Assume liter- to gallon-sized, non-breakable containers	Reasonably Probable	Marginal: Injury to a worker (burns)	Chemical-resistant flooring, activities in fume hood	Remote	Marginal; Injury to a worker (burns)	Moderate Risk / Low Risk
HBML-4	Hydrogen	Release of hydrogen followed by ignition	100 feet of 1/8-inch ID tubing at 150 psig	Occasional	Critical: Potential for flash fire, injury to workers	Flammable-gas detectors, laboratory ventilation, emergency shutoff valves	Impossible	Negligible: Release with no fire, very small flammable volume in vicinity of break	Moderate Risk / Routine Risk AI: Size of supply line and pressure, before and after pressure reduction
HBML-5	Hydrogen	Release of hydrogen into an enclosure followed by deflagration	Buildup to flammable concentration in enclosure within room	Occasional	Catastrophic: Deflagration inside enclosure would produce shrapnel, which could seriously injure an individual and damage adjacent equipment	Flammable-gas detectors, rapid shutoffs on hydrogen supply line, design limits on quantity of hydrogen that could be released before shutoff	Occasional	Marginal: Might still be a small fire that would have the potential for some minor injuries and equipment damage	High Risk / Low Risk AI: Need design commitment that limits the amount of hydrogen release if a pipe breached, and the design does not have enclosures where the hydrogen can accumulate

Event Scenarios[a]

Scenario Number	Laboratory/ Energy Source	Hazard(s)	Quantity	Likelihood of Occurrence	Severity	Possible Preventive/ Protective/ Mitigative Measures	Likelihood of Occurrence	Severity	Risk Level (Without Safety Features/ With Safety Features) Comments
				Without Safety Features			With Safety Features		
HBML-6	Natural gas	Release of natural gas followed by ignition	Size of supply line and pressure not specified, assume 1: OD and low pressure, < 15 psig	Occasional	Critical: Potential for flash fire, injury to workers	Flammable-gas detectors, laboratory ventilation, emergency shutoff valves	Impossible	Negligible: Release with no fire	Bounded by HBML-4 AI: Size of Supply line and supply pressure
HBML-7	Flammable liquid	Spill or discharge of flammable liquid	Size of supply line and pressure not specified, assume 1-inch OD and <15 psig pressure	Occasional	Critical: Potential for fire and injury to workers	Spill prevention program, emergency shutoff valves	Extremely Remote	Negligible: Release with no fire	Bounded by HBML-4 AI: Size of storage vessels
HBML-8	High voltage and current	Energy discharge cuts through hydrogen gas line	100 feet of 0.109-inch ID hydrogen at 150 psig ignites	Reasonably Probable	Catastrophic: Room fire involving hydrogen – potential loss of laboratory	Emergency shutoff valves on hydrogen lines on loss of pressure, separation of electrical equipment from flammable gas lines, isolation valves	Impossible	Negligible: Limited quantify of hydrogen - line not in vicinity of electrical discharge	High Risk / Routine Risk

Event Scenarios[a]

Scenario Number	Laboratory/ Energy Source	Hazard(s)	Quantity	Likelihood of Occurrence	Severity	Possible Preventive/ Protective/ Mitigative Measures	Likelihood of Occurrence	Severity	Risk Level (Without Safety Features/ With Safety Features) Comments
				Without Safety Features			With Safety Features		
High Bay Lab Environmental Test Chambers									
HBTC-1	Vehicle exhaust	Exposure to toxic gas	Typical rate of CO from vehicle exhaust (assume 200-hp engine)	Remote	Critical: Personnel could be overcome by toxic gases (CO), resulting in a fatality	Vented exhaust, toxic gas monitoring equipment interlocked to shut down engine if toxic gas detected	Impossible	Marginal: If overcome, co-worker would rescue	Low Risk / Routine Risk
HBTC-2	Biodiesel fuel	Diesel spill and fire when it comes in contact with hot surface	250-gallon supply	Remote	Critical: Loss of test vehicle, damage to environmental chamber	Secondary containment, fire suppression	Remote	Negligible: Some damage to test vehicle	Low Risk / Routine Risk
HBTC-3	Hydrogen and natural gas	Flammable gas buildup from leak in hydrogen or natural gas supply line	Vehicle-sized enclosure	Remote	Catastrophic: Explosion of test chamber from flammable gas buildup, possible worker fatality	Exhaust ventilation, toxic gas analysis, IR/UV detection, automatic shutoff valves, welded or metal-gasketed fittings	Extremely Remote	Marginal: Hydrogen leak could cause fire within test chamber that is quickly brought under control without major equipment damage	Moderate Risk / Routine Risk AI: The quantity of H_2 in the piping between the shutoff valve and the motor must not be sufficient to generate a flammable atmosphere in the vehicle enclosure

Event Scenarios[a]

Scenario Number	Laboratory/ Energy Source	Hazard(s)	Quantity	Likelihood of Occurrence (Without Safety Features)	Severity (Without Safety Features)	Possible Preventive/ Protective/ Mitigative Measures	Likelihood of Occurrence (With Safety Features)	Severity (With Safety Features)	Risk Level (Without Safety Features/ With Safety Features) Comments
HBTC-4	Overhead gantry crane	Equipment or tool drop from crane cable break	10 to 20 tons	Remote	Critical: Personnel injury (possibly a fatality) from a cable break, equipment damage	Periodic weight testing and replacement when signs of cable wear appear, standard industrial safety procedures	Extremely Remote	Negligible: No injury to personnel or equipment damage	Low Risk / Routine Risk
Commercial Building High Bay Laboratory									
		Hazards similar to those addressed under the High Bay - Main Laboratory							
Environmental Test Chamber in High Bay									
High Bay Laboratory – VSHOT									
SHOT-1	Overhead gantry crane	Equipment or tool drop from crane cable break	10 tons	Remote	Critical: Personnel injury (possibly a fatality) from a cable break	Periodic weight testing and replacement when signs of cable wear appear, standard industrial safety procedures	Impossible	Marginal: No injury to personnel or equipment damage	Low Risk / Routine Risk
High Bay Control Room									
HBCR-1	Electricity	Standard industrial hazard							

Event Scenarios[a]

Scenario Number	Laboratory/ Energy Source	Hazard(s)	Quantity	Likelihood of Occurrence	Severity	Possible Preventive/ Protective/ Mitigative Measures	Likelihood of Occurrence	Severity	Risk Level (Without Safety Features/ With Safety Features) Comments
				Without Safety Features			With Safety Features		
High Voltage / High Current Laboratory; High Voltage / High Current Research Fuel Lines (hydrogen, natural gas, diesel and biodiesel)									
HVHC-1	Electricity	Explosive destruction of test device from high current or voltage	Shrapnel from test device destruction	Reasonably Probable	Catastrophic: Shrapnel could severely injure workers, gas expansion from destruction of equipment could destroy room	Explosive-proof construction, remote testing in specially designed and isolated room, no ancillary personnel or equipment in test room	Reasonably Probable	Negligible	High Risk / Routine Risk
HVHC-2	Room Fire	Failure of test device could damage fuel supply line, initiating a room fire	Flammable gas and liquid supply lines (Research Fuel Lines) provide fuel source for fire	Occasional	Critical: Fire could damage equipment in laboratory	Placement of test device in a containment chamber or vented chamber?	Remote	Marginal: Could still damage equipment in room from test piece destruction	Moderate Risk / Low Risk AI: Do not understand need for fuel supply lines in High Voltage / High Current Lab
HVHC-3	Electricity	An electrical short	Arc Flash from an electrical short	Reasonably Probable	Critical Flash could burn or cause eye damage to workers	Placement of barriers between workers and high voltage high current equipment	Remote	Negligible Separation of workers from high voltage high current equipment prevents injury	High Risk / Routine Risk
Power Electronics Laboratory Research Fuel Lines (hydrogen, natural gas, diesel and biodiesel), High Voltage and High Current									
PEL-1	Electricity	Standard industrial hazard							

Event Scenarios[a]

Scenario Number	Laboratory/ Energy Source	Hazard(s)	Quantity	Likelihood of Occurrence	Severity	Possible Preventive/ Protective/ Mitigative Measures	Likelihood of Occurrence	Severity	Risk Level (Without Safety Features/ With Safety Features) Comments
				Without Safety Features			With Safety Features		
PEL-2	Hydrogen gas	Room deflagration from hydrogen gas buildup		Reasonably Probable	Catastrophic: Damage to laboratory equipment and serious injury to workers	Room ventilation, flammable gas detectors with alarm	Extremely Remote	Negligible: No damage to personnel or equipment	High Risk / Routine Risk AI: Need data on hydrogen gas supply line
PEL-3	Natural gas	Room deflagration from natural gas buildup		Reasonably Probable	Bounded by PEL-2				AI: Need information on natural gas line
Smart Grid Components Laboratory									
SGC-1	Electricity	Arcing from equipment failure (electrical short)	480-V, 30-amp three-phase equipment	Reasonably Probable	Critical: Could injure workers exposed to the flash (burns) and damage equipment	Safe operating procedures, protective barriers for operating personnel, equipment design to minimize likelihood of shorting, trained and qualified personnel, blowout panels to prevent room over-pressurization from heating	Remote	Marginal: Still could be loss of equipment from event	High Risk / Low Risk

Event Scenarios[a]

Scenario Number	Laboratory/ Energy Source	Hazard(s)	Quantity	Likelihood of Occurrence (Without Safety Features)	Severity (Without Safety Features)	Possible Preventive/ Protective/ Mitigative Measures	Likelihood of Occurrence (With Safety Features)	Severity (With Safety Features)	Risk Level (Without Safety Features/ With Safety Features) Comments
Instruments Developments Laboratory									
IDL-1	Electricity and small quantities of chemicals	Standard laboratory hazards				Standard laboratory ventilation to prevent accumulation of chemical vapors			
Electrical Shop									
ES-1	Electricity	Standard industrial hazard							
Hydrogen Production Laboratory Research Fuel Lines									
HPL-1	Hydrogen gas	Hydrogen release from break in electrolyzer piping	Hydrogen generated at a rate of 3,000 standard liters/minute based on a 1-MW electrolyzer	Reasonably Probable	Catastrophic: Personnel injury (burns) from deflagration of hydrogen gas cloud	Periodic inspection and maintenance, gas detectors with alarms, electrolyzer shutoff, ventilation system to prevent buildup of flammable gases	Extremely Remote	Negligible: With an open pipe, it takes almost 20 minutes to build up to a flammable gas concentration in room, ample time to detect and take corrective actions	High Risk / Routine Risk

Event Scenarios[a]

Scenario Number	Laboratory/ Energy Source	Hazard(s)	Quantity	Likelihood of Occurrence	Severity	Possible Preventive/ Protective/ Mitigative Measures	Likelihood of Occurrence	Severity	Risk Level (Without Safety Features/ With Safety Features) Comments
				Without Safety Features			With Safety Features		
HPL-2	Electrolyzer explosion because of overpressure (system failure isolates electrolyzer or compressor back flow)	Release of oxygen, hydrogen, and caustic spray	Electrolyzers operate at 200 psia (temperature not specified)	Reasonably Probable	Catastrophic: Personnel injury from shrapnel, damage to adjacent equipment, explosive gas cloud	Design of electrolyzer, overpressure cutoff, pressure relief valve, over-temperature cutoff	Extremely Remote	Marginal: Could still be the possibility of an injury and a small amount of damage from the initiating event	High Risk / Routine Risk
HPL-3	Electrolyzer explosion because of overpressure	Caustic spray when electrolyzer overpressure disk ruptures	Not specified	Reasonably Probable	Critical: Personnel injury from caustic spray	Design of electrolyzer, overpressure cutoff, pressure relief valve, over-temperature cutoff	Remote	Negligible: Worker shielded from spray	High Risk / Routine Risk AI: Need quantity and temperature of caustic to better quantify consequences
HPL-4	Electrolyzer temperature excursion because of membrane rupture	Reaction of hydrogen and oxygen produces heat and pressure, rupturing the electrolyzer	Electrolyzers operates at 200 psi	Remote	Critical: Personnel injury (caustic spray) and shrapnel, damage to adjacent equipment, explosive gas cloud	Electrolyzer design, pressure-relief valve?, temperature interlock, pressure interlock.	Extremely Remote	Critical: Personnel injury (caustic spray) and shrapnel, damage to adjacent equipment, explosive gas cloud	Low Risk / Low Risk: Small pinholes would lead to over-temperature shutdown

Event Scenarios[a]

Scenario Number	Laboratory/ Energy Source	Hazard(s)	Quantity	Likelihood of Occurrence	Severity	Possible Preventive/ Protective/ Mitigative Measures	Likelihood of Occurrence	Severity	Risk Level (Without Safety Features/ With Safety Features) Comments
				Without Safety Features			With Safety Features		
HPL-5	Compressor failure	Flying shrapnel	Shrapnel from explosion of 1-liter vessel at 3,500 psi	Remote	Critical: Personnel injury, equipment damage	Compressor design, compressor outside work area, shielded from hydrogen fueling station where personnel are present	Remote	Marginal Personnel injury, damage to equipment	Low Risk / Low Risk: Specifically stated indoor and no enclosure
HPL-6	High-pressure hydrogen	Backflow of 3,500 (in HPL) to 15,000 psi hydrogen gas (outside building) overpressures equipment or piping	Nominally 200 kg at various pressures	Reasonably Probable	Catastrophic: Rapid buildup of hydrogen in High Pressure Laboratory, probable room deflagration	Compressor design to prevent backflow, inside tubing rated at 20,000 psi	Extremely Remote	Negligible: No damage to equipment or release of hydrogen gas to High Pressure Laboratory	High Risk / Routine Risk
HPL-7	Flammable liquids	Fire involving flammable materials – possible failure of high-pressure hydrogen line in fire	Not specified	Reasonably Probable	Catastrophic: Potential for severe injury to personnel, loss of High Pressure Laboratory	Layout of equipment to prevent exposure of high-pressure lines to fire, low combustible loading	Remote	Marginal: Small fire could damage some equipment	High Risk / Low Risk AI: Need quantity of flammable liquids present in HPL

Event Scenarios[a]

Scenario Number	Laboratory/ Energy Source	Hazard(s)	Quantity	Likelihood of Occurrence (Without Safety Features)	Severity (Without Safety Features)	Possible Preventive/ Protective/ Mitigative Measures	Likelihood of Occurrence (With Safety Features)	Severity (With Safety Features)	Risk Level (Without Safety Features/ With Safety Features) Comments
Hydrogen Systems Laboratory and Hydrogen Systems Outdoor Test Area Research Fuel Lines (hydrogen, natural gas, diesel, and biodiesel)									
OTP-1	Hydrogen gas	Catastrophic rupture of high-pressure hydrogen storage vessel	25 kg of hydrogen at 3,500 to 15,000 psi	Reasonably Probable	Catastrophic: Damage to adjacent equipment and buildings, serious injury (perhaps a fatality) to nearby personnel	ICC, NFPA, ASME pressure vessel codes, pressure relief devices on storage vessels, separation distance from buildings and other equipment, restricted access to storage vessels (e.g., NFPA 55)	Extremely Remote	Marginal: Some equipment damage	High Risk / Routine Risk AI: Need to provide adequate separation distance from building to prevent shrapnel damage and protect nearby personnel
OTP-2	Hydrogen gas	Compressor failure	Compressor raising the pressure to as high as 15,000 psi	Reasonably Probable	Critical: Personnel injury (including possible fatality), damage to facility and equipment from shrapnel, deflagration of flammable gas cloud from hydrogen release when compressor fails	ASME design standards, required periodic inspection and maintenance, establishing a safe distance from any structures	Extremely Remote	Critical: Personnel injury (including possible fatality), damage to facility and equipment from shrapnel, deflagration of flammable gas cloud from hydrogen release when compressor fails	High Risk / Low Risk: Bounded by event scenario for compressor failure under High Pressure Test Facility

Event Scenarios[a]

Scenario Number	Laboratory/ Energy Source	Hazard(s)	Quantity	Likelihood of Occurrence	Severity	Possible Preventive/ Protective/ Mitigative Measures	Likelihood of Occurrence	Severity	Risk Level (Without Safety Features/ With Safety Features) Comments
				Without Safety Features			With Safety Features		
OTP-3	Hydrogen gas	Flammable gas cloud from hydrogen leak	200 kg of hydrogen at 3,500 to 15,000 psi	Remote	Critical: Personnel injury (burns) from deflagration of hydrogen gas cloud	Welded or metal pipe joints, leak testing, selection of materials that are compatible with high-pressure hydrogen without embrittlement, periodic inspection and maintenance	Extremely Remote	Marginal: Personnel injury (burns) from deflagration of hydrogen gas cloud	Low Risk / Routine Risk: Hydrogen gas rapidly diffusing upward limits the size of the flammable cloud, confined spaces for accumulation should be avoided
OTP-4	Grass fire	Grass fire heats hydrogen storage vessels, causing pressure relief valve to vent H_2 gas	Approximately 200 kg of hydrogen stored	Reasonably Probable	Catastrophic: Some vessels may fail destructively if fire impacts end of vessels opposite relief valves	Good housekeeping that keeps combustible debris away from vessel storage areas, vent pipes on relief valves to discharge hydrogen gas at an elevated point (where it would not add to the fire energy)	Remote	Negligible: No fire and no damage from a fire	High Risk / Routine Risk AI: Need to direct venting hydrogen away from equipment and buildings and need to confine rupture disk so no personnel injuries occur

Event Scenarios[a]

Scenario Number	Laboratory/ Energy Source	Hazard(s)	Quantity	Likelihood of Occurrence	Severity	Possible Preventive/ Protective/ Mitigative Measures	Likelihood of Occurrence	Severity	Risk Level (Without Safety Features/ With Safety Features) Comments
				Without Safety Features			With Safety Features		
OTP-5	Hydrogen gas	Hydrogen buildup on enclosure followed by deflagration when ignition source introduced	Sufficient hydrogen to reach the 4-percent flammable limit in the enclosure	Reasonably Probable	Catastrophic: Potential for serious injury to workers and major damage to the ESIF	Welded piping, flammable-gas detectors with shutoff interlock on hydrogen supply line	Remote	Negligible: No buildup of hydrogen gas in the test enclosure	High Risk / Routine Risk
OTP-6	Electrical energy release	Short in electrical equipment burns hole in high-pressure hydrogen line	600 V ac and 600 V dc plus hydrogen at pressures from 3,500 to 12,000 psi	Occasional	Catastrophic: Potential for serious injury and loss of facility from hydrogen fire	Separation of electrical power systems from hydrogen supply piping and hydrogen storage systems	Extremely Remote	Marginal: Some equipment damage could still occur from electrical short	High Risk / Routine Risk
OTP-7	Hydrogen gas	Hydrogen fire during vehicle filling because connection is not leak-tight	Release of 10,000 psi hydrogen from filling station	Frequent	Critical: Burns to individual filling vehicle, fire spreads to vehicle and occupants	EPA / NFPA collaboration to develop first safety standard for hydrogen refilling stations	Remote	Marginal: A few small fires could still occur, dispenser system designed to be resistant to hydrogen fires	High Risk / Low Risk
OTP-8	Hydrogen gas	Hydrogen air mixture detonates within the storage vessel during filling	A flammable mixture of air and hydrogen present in the storage vessel	Remote	Catastrophic: Rupture of adjacent storage vessels, generation of shrapnel extending the damage radius for personnel and equipment	Evacuation of the air before starting to fill the pressure vessels with hydrogen	Extremely Remote	Catastrophic: Rupture of adjacent storage vessels, generation of shrapnel extending the damage radius for personnel and equipment	Moderate Risk / Low Risk

Event Scenarios[a]

Scenario Number	Laboratory/ Energy Source	Hazard(s)	Quantity	Likelihood of Occurrence (Without Safety Features)	Severity (Without Safety Features)	Possible Preventive/ Protective/ Mitigative Measures	Likelihood of Occurrence (With Safety Features)	Severity (With Safety Features)	Risk Level (Without Safety Features/ With Safety Features) Comments
OTP-9	Hydrogen gas	Failure of a research component generates shrapnel and hydrogen fire	Several hundred kilograms of hydrogen and many pieces of equipment operating at high pressure	Remote	Catastrophic: Damage from the failure of one piece of equipment could result in the failure of other pieces of equipment	Safe separation distances (verify that distances in NFPA 55 are applicable), limit occupancy to protect visitors and workers from flying debris	Remote	Critical: Damage limited to failed piece of equipment	Moderate Risk / Low Risk
Roof Test Area									
RTA-1	Propylene glycol	Leak of propylene glycol	Leak rate unspecified - release to environment expected to be minimal						Routine Risk: Bounded by other events
Machine Shop Acetylene and oxygen, argon from gas bottles									
MS-1	Rotating equipment	Standard industrial hazard							

Event Scenarios[a]

Scenario Number	Laboratory/ Energy Source	Hazard(s)	Quantity	Likelihood of Occurrence	Severity	Possible Preventive/ Protective/ Mitigative Measures	Likelihood of Occurrence	Severity	Risk Level (Without Safety Features/ With Safety Features) Comments
				Without Safety Features			With Safety Features		
MS-2	Acetylene deflagration	Acetylene released from storage cylinder	Standard welding tank (acetylene dissolved in acetone)	Remote	Catastrophic: Acetylene shares many of the same properties as hydrogen but would not readily disperse, so would deflagrate or, when confined, detonate, damaging equipment or injuring workers	Dangers of acetylene well understood, concern arises during maintenance when equipment is moved into an area with other hazards such as high-pressure hydrogen storage tanks	Extremely Remote	Marginal	Moderate Risk / Routine Risk
Energy Storage Laboratory		Research Fuel Lines (hydrogen, natural gas, diesel, and biodiesel)							
ESL-1	Hydrogen	Hydrogen buildup from outgassing of batteries	Unspecified rate of generation - expected to be low	Frequent	Catastrophic: Deflagration of hydrogen could fail walls of storage area and cause fires in adjacent laboratories, also serious injuries to personnel	Flammable-gas detectors, laboratory ventilation	Extremely Remote	Negligible: Discharge rate is expected to very slow, so room ventilation would keep hydrogen gas concentration well below detection limits	High Risk / Routine Risk AI: Laboratory design should ensure that hydrogen cannot build up in a battery room

Event Scenarios[a]

Scenario Number	Laboratory/ Energy Source	Hazard(s)	Quantity	Likelihood of Occurrence	Severity	Possible Preventive/ Protective/ Mitigative Measures	Likelihood of Occurrence	Severity	Risk Level (Without Safety Features/ With Safety Features) Comments
				Without Safety Features			With Safety Features		
ESL-2	H_2S gas release from overcharging batteries	Toxic gas release	H_2S formed at rate based on charging current	Reasonably Probable	Critical: Personnel could be overcome by H_2S gas	Batteries protected from overcharging, room ventilation, alarm when ventilation stops	Extremely Remote	Negligible: No damage from overcharging, no release of H_2S gas	High Risk / Routine Risk AI: Need charge rate of batteries
ESL-3	Sulfuric acid	Sulfuric acid release from pressure buildup in battery	Small spray of concentrated sulfuric acid	Reasonably Probable	Marginal: Sulfuric acid has a low vapor pressure, so injury to personnel expected to be minor	Acid-resistant floors and paint, sturdy racks that are resistant to sulfuric acid, safe handling practices for acids and bases	Extremely Remote	Negligible: No damage if spills are prevented	Moderate Risk / Routine Risk AI: Need estimated quantity of sulfuric acid in batteries
Electrical Visualization									
EV-1	Standard electrical hazards								
ZEB Simulation Laboratory									
ZS-1	Standard electrical hazards								

Event Scenarios[a]

Scenario Number	Laboratory/ Energy Source	Hazard(s)	Quantity	Likelihood of Occurrence (Without Safety Features)	Severity (Without Safety Features)	Possible Preventive/ Protective/ Mitigative Measures	Likelihood of Occurrence (With Safety Features)	Severity (With Safety Features)	Risk Level (Without Safety Features/ With Safety Features) Comments
Thermal Storage Materials Laboratory									
TS-1	Nanomaterials	Release of nanomaterials to room	Less than 10 grams, probably on a solid substrate	Unknown		DOE / NIOSH guidelines for safe handling of nanomaterials, inerted glovebox or transport in closed container with taped lid	Extremely Remote	Marginal because of uncertainty, could be unknown hazards	Routine Risk
Thermal Storage Processes and Components Laboratory									
TP-1	Nanomaterials	Release of nanomaterials to room	Less than 10 grams, probably carbon-based and probably on a solid substrate	Unknown		DOE / NIOSH guidelines for safe handling of nanomaterials, inerted glovebox or transport in closed container with taped lid	Extremely Remote	Marginal because of uncertainty, could be unknown hazards	Routine Risk
TP-2	Hot heat transfer fluids	Burns from exposure to release of heat transfer	Quantity and temperature not mentioned	Reasonably Probable	Critical: Exposure to high temperature	Noncorrosive construction materials, periodic inspection and maintenance	Remote	Negligible: Minimal loss of heat transfer fluid	High Risk / Routine Risk

Event Scenarios[a]

Scenario Number	Laboratory/ Energy Source	Hazard(s)	Quantity	Likelihood of Occurrence	Severity	Possible Preventive/ Protective/ Mitigative Measures	Likelihood of Occurrence	Severity	Risk Level (Without Safety Features/ With Safety Features) Comments
				Without Safety Features			With Safety Features		
TP-3	High electrical loads	Potential for shorts causing electrical discharges	480 V ac, 100 kW of power	Reasonably Probable	Critical: Personnel exposure to burns from arc discharge	Equipment built to electrical standards	Remote	Negligible: Standards protect individuals from injury when short occurs	High Risk / Routine Risk
Outdoor Test Beds – partially covered under Hydrogen Systems Laboratory and Hydrogen Systems Outdoor Test Area									
OTB-1	Diesel fuel	Spill and fire while filling diesel fuel	1,000-gallon diesel storage tank	Remote	Catastrophic: Boiling liquid expanding vapor explosion (BLEVE) involving diesel storage tank	Design of tank vents and leg supports, dike designed to prevent pooling under tank	Extremely Remote	Marginal: Fire involving diesel fuel during filling of tank	Moderate Risk / Routine Risk
Metrology Laboratory									
Electrical Calibration Laboratory									
ECL-1	Standard laboratory hazards								
Shielded Room									
SR-1	Standard laboratory hazards, including a N_2 gas bottle								
Optical Calibration Laboratory									
OCL-1	Standard laboratory hazards								

Event Scenarios[a]

Scenario Number	Laboratory/ Energy Source	Hazard(s)	Quantity	Likelihood of Occurrence (Without Safety Features)	Severity (Without Safety Features)	Possible Preventive/ Protective/ Mitigative Measures	Likelihood of Occurrence (With Safety Features)	Severity (With Safety Features)	Risk Level (Without Safety Features/ With Safety Features) Comments
Equipment Staging Area and Heat Sink (airlock)									
ESL-1	Standard laboratory hazards								
Hydrogen Technologies and Systems Center Manufacturing Laboratory									
ML-1	Solvents	Small local fire in work area	Assume liter- to gallon-sized, nonbreakable containers	Reasonably Probable	Marginal: Injury to a worker (burns), possible loss of equipment	Low combustible loading, solvents used in fume hood	Remote	Negligible: Minimal equipment damage, minor worker injury	Moderate Risk / Routine Risk
ML-2	X-ray equipment	Accidental X-ray exposure	Unspecified energy level, but below the level that would be capable of life-threatening exposures in minutes	Remote	Marginal: X-ray exposure may exceed annual limit of 3 rem	Personnel shielding, barriers, alarms (audible and/or lights) when X-ray tube active	Extremely Remote	Negligible: Minor exposure far below regulatory limits	Low Risk / Routine Risk
MEA Laboratory									
MEA-1	Standard laboratory hazards								

Event Scenarios[a]

Scenario Number	Laboratory/ Energy Source	Hazard(s)	Quantity	Likelihood of Occurrence (Without Safety Features)	Severity (Without Safety Features)	Possible Preventive/ Protective/ Mitigative Measures	Likelihood of Occurrence (With Safety Features)	Severity (With Safety Features)	Risk Level (Without Safety Features/ With Safety Features) Comments
Sensor Laboratory High-pressure hydrogen up to 1,000 psi in equipment – may be 2,500 psi in gas cylinders)									
SL-1	Hydrogen gas	Breach of high-pressure hydrogen gas piping operating at 1,000 psi	Choke flow through 0.25-inch OD high-pressure tubing w/ 0.109-inch ID	Occasional	Catastrophic: Rapid release of hydrogen into laboratory would rapidly raise concentration to above flammable limit, causing deflagration in room	High flow detectors to isolate hydrogen storage vessels, welded piping, routine maintenance and inspection, room ventilation	Extremely Remote	Critical: Assume a 50-psig drop across 100 feet of tubing would not trigger automatic shutoff, and flow would still allow hydrogen concentration in room to build up quickly	High Risk / Low Risk. AI: Is the hydrogen piping connected to hydrogen storage system or just a gas bottle of hydrogen. How much hydrogen could be released?
High Pressure Test Facility 10,000 psi nitrogen, 15,000 psig hydrogen									
HPTF-1	Hydrogen gas	Compressor failure	Compressor raising the pressure to as high as 15,000 psi	Remote	Critical: Personnel injury (including possible fatality), damage to facility and equipment from shrapnel, deflagration of flammable gas cloud from hydrogen release when compressor fails	ASME design standards, required periodic inspection and maintenance	Extremely Remote	Critical: Personnel injury (including possible fatality), damage to facility and equipment from shrapnel, deflagration of flammable gas cloud from hydrogen release when compressor fails	Moderate Risk / Low Risk

Event Scenarios[a]

Scenario Number	Laboratory/ Energy Source	Hazard(s)	Quantity	Likelihood of Occurrence (Without Safety Features)	Severity (Without Safety Features)	Possible Preventive/ Protective/ Mitigative Measures	Likelihood of Occurrence (With Safety Features)	Severity (With Safety Features)	Risk Level (Without Safety Features/ With Safety Features) Comments
HPTF-2	Hydrogen gas	Hydrogen gas leak	Hydrogen gas at 15,000 psi in piping and equipment	Remote	Critical: Personnel injury (including possible fatality), deflagration of flammable gas cloud from hydrogen release	ASME design standards, required periodic inspection and maintenance, flammable-gas detectors	Extremely Remote	Critical: Personnel injury (including possible fatality), deflagration of flammable gas cloud from hydrogen release	Low Risk / Low Risk
HPTF-3	Hydrogen gas	Rupture of surge tank on compressor	Hydrogen gas at 15,000 psi in vessel	Remote	Bounded by compressor failure	ASME design standards, required periodic inspection and maintenance			
HPTF-4	Helium or Nitrogen gas	Rupture of hydrogen pressure vessel in High Pressure Test Cell – equivalent energy release 2.5 kg TNT	Helium or Nitrogen gas at 10,000 psi in 163-liter vessel	Frequent	Catastrophic: Tank failure produces shrapnel that damages laboratory and fatally injures personnel	High Pressure Test Cell designed to contain pressure increase from helium or nitrogen release and debris from vessel failure	Frequent	Negligible: Chamber designed to confine the nitrogen and debris from vessel explosion	High Risk / Routine Risk

Event Scenarios[a]

Scenario Number	Laboratory/ Energy Source	Hazard(s)	Quantity	Likelihood of Occurrence (Without Safety Features)	Severity (Without Safety Features)	Possible Preventive/ Protective/ Mitigative Measures	Likelihood of Occurrence (With Safety Features)	Severity (With Safety Features)	Risk Level (Without Safety Features/ With Safety Features) Comments
PEC Advanced Materials Laboratory									
AM-1	Solvents	Small local fire in work area	Assume liter- to gallon-sized, nonbreakable containers	Reasonably Probable	Marginal: Injury to a worker (burns), possible loss of equipment	Low combustible loading, solvents used in fume hood	Remote	Negligible: Minimal equipment damage, minor worker injury	Moderate Risk / Routine Risk
AM-2	Solvents	Room fire	Assume many liter- to gallon-sized bottles in storage cabinets	Occasional	Marginal: Equipment damage, life-threatening worker injury from burns and toxic smoke exposure (from corrosives in fire)	Nonflammable storage cabinets, flammable-gas monitors	Impossible	Negligible: Exposed flammable materials would be insufficient to engulf the entire room, minimal equipment damage, minor worker injury	Low Risk / Routine Risk
AM-3	Corrosives	Small spill of corrosives in work area	Assume liter- to gallon-sized, nonbreakable containers	Reasonably Probable	Marginal: Injury to a worker (burns)	Berm and chemical-resistant flooring, activities in fume hood	Remote	Negligible: Minor worker injury	Moderate Risk / Routine Risk

Event Scenarios[a]

Scenario Number	Laboratory/ Energy Source	Hazard(s)	Quantity	Likelihood of Occurrence	Severity	Possible Preventive/ Protective/ Mitigative Measures	Likelihood of Occurrence	Severity	Risk Level (Without Safety Features/ With Safety Features) Comments
				Without Safety Features			With Safety Features		
AM-4	Incompatible reactions of solvents with acids	Heat of reaction, pressure buildup and container rupture, toxic gas release	Assume liter- to gallon-sized, nonbreakable containers	Reasonably Probable	Critical: Chemical burns and toxic gas exposure could result in permanent health effects to exposed workers	Personnel training, laboratory safety procedures such as face shields, fume hoods, gloves, materials handled would not have runaway interactions	Remote	Marginal: Chemical reactions limited to heat generation, a small amount of toxic gas generation handled by fume hood, perhaps small spills resulting in minor injuries	High Risk / Low Risk
AM-5	Drop and spill of container with nanomaterials	Nanomaterials can be absorbed through the skin or be inhaled and enter the blood stream in the lungs	Quantity less than 10 grams, carbon-based, typically immobilized on a solid substrate	Reasonably Probable	Critical: Potential exposure to hazards that are not totally known	Handled in gloveboxes or in closed and taped containers during transfer, HEPA filtration of room exhaust, follow NIOSH guide	Remote	Marginal: NIOSH protection guide should minimize hazards, even though hazards not totally understood	High Risk / Low Risk
AM-6	Drop of nanomaterials generates a flammable gas cloud that ignites	Glovebox failure from internal deflagration	Quantity less than 10 grams, typically immobilized on a solid substrate	Occasional	Critical: Potential worker injury from flying debris	Inert glovebox, HEPA filtration of exhaust from laboratory and gloveboxes, where nanomaterials are generated or handled	Extremely Remote	Critical: Potential worker injury from flying debris	High Risk / Low Risk

Event Scenarios[a]

Scenario Number	Laboratory/ Energy Source	Hazard(s)	Quantity	Likelihood of Occurrence (Without Safety Features)	Severity (Without Safety Features)	Possible Preventive/ Protective/ Mitigative Measures	Likelihood of Occurrence (With Safety Features)	Severity (With Safety Features)	Risk Level (Without Safety Features/ With Safety Features) Comments
Fuel Cell Laboratory	Research Fuel Lines (hydrogen, natural gas, diesel, and biodiesel)								
FCL-1	Hydrogen	Pipe or vessel leak followed by room deflagration	50 standard liters per minute	Occasional	Catastrophic: Injury to personnel from flash burns, equipment damage from subsequent room fire	Volume of room, room ventilation, flammable-gas detectors, excess-flow valve	Extremely Remote	Negligible: Given the maximum rate of leakage and the room ventilation rate, it should be possible to design laboratory to prevent a flammable gas buildup	High Risk / Routine Risk AI Need to ensure that the hydrogen cannot build up in an enclosed space
FCL-2	Hydrogen - oxygen	Fuel cell membrane rupture and resultant oxygen - hydrogen explosion	Volume in cell limited to 10 milliliters (ml)	Occasional	Critical: Rupture of fuel cell and injury to personnel from hot flying debris	Cell casing design to contain explosion	Extremely Remote	Negligible: Fuel cell casing can be designed to contain such an explosion	Moderate Risk / Routine Risk Could calculate the TNT equivalent for a 10-ml vessel failing at 150 psi, the maximum pressure generated by the explosive reaction

Event Scenarios[a]

Scenario Number	Laboratory/ Energy Source	Hazard(s)	Quantity	Likelihood of Occurrence (Without Safety Features)	Severity (Without Safety Features)	Possible Preventive/ Protective/ Mitigative Measures	Likelihood of Occurrence (With Safety Features)	Severity (With Safety Features)	Risk Level (Without Safety Features/ With Safety Features) Comments
FCL-3	Toxic gases	Pipe or vessel leak	Volume of standard gas cylinder (CO concentration > 1 percent) or a small lecture bottle of 100 percent CO	Reasonably Probable	Critical: Possible accumulation of CO, leading to irreversible health effects	Gas detectors, laboratory ventilation	Extremely Remote	Negligible: With warning and dilution from air exchanges, the concentration of CO is probably below level for continuous occupancy	High Risk / Routine Risk AI: Need to verify that for worst-case leaks, the ventilation system maintains the CO concentration at safe levels
Fuel Quality Laboratory									
FQL-1	Hydrogen sulfide lecture-sized gas bottle	Drop and shearing off of valve stem	Gas release from 2,000 psi bottle	Occasional	Critical: Possible injury to personnel from rocketing bottle, exposure to toxic gas cloud	Design of gas storage bottles, safe laboratory handling procedures, use of bottle small enough to limit impacts	Extremely Remote	Marginal: Smaller rocketing bottles could still injure personnel, although impact and velocity would be less	Moderate Risk / Routine Risk
FQL-2	Carbon monoxide release	Toxic gas leak	Gas leak in piping	Reasonably Probable	Critical: Personnel exposed to CO could experience life-threatening health effects, even death	Design and inspection of piping integrity, gas monitors, laboratory ventilation	Extremely Remote	Negligible: Ventilation of laboratory should minimize CO concentration, gas monitors should warn laboratory occupants to leave a toxic environment.	High Risk / Routine Risk AI: Design of laboratory should ensure that CO cannot collect in confined spaces

Event Scenarios[a]

Scenario Number	Laboratory/ Energy Source	Hazard(s)	Quantity	Likelihood of Occurrence — Without Safety Features	Severity — Without Safety Features	Possible Preventive/ Protective/ Mitigative Measures	Likelihood of Occurrence — With Safety Features	Severity — With Safety Features	Risk Level (Without Safety Features/ With Safety Features) Comments
FQL-3	Gases in standard gas storage bottles	Drop and shearing off of valve stem	Gas bottle rockets around the laboratory, can reach velocities of greater than 100 mph	Occasional	Critical: Possible injury to personnel (including possible fatality), extensive damage to laboratory equipment	Design of gas storage bottles, safe laboratory handling procedures	Extremely Remote	Critical: Possible injury to personnel (including possible fatality), extensive damage to laboratory equipment	High Risk / Low Risk
FQL-4	Gases in standard gas storage bottles	Drop and shearing off of valve stem	Flammable gas cloud formed from sudden release	Occasional	Catastrophic: Possible deflagration, injury to personnel from flash burns, extensive damage to laboratory from overpressure	Design of gas storage bottles safe laboratory handling procedures	Extremely Remote	Negligible: Size of laboratory should limit concentration to below the flammable limit for all cases	High Risk / Routine Risk Need to analyze the final concentration assuming complete mixing when the contents of a standard gas cylinder is rapidly emptied into the laboratory.
FQL-5	Solvents	Small local fire in work area	Assume liter- to gallon-sized, nonbreakable containers	Reasonably Probable	Marginal: Injury to a worker (burns), possible loss of equipment	Low combustible loading, solvents used in fume hood	Remote	Marginal: Minimal equipment damage, minor worker injury	Moderate Risk / Routine Risk

Event Scenarios[a]

Scenario Number	Laboratory/ Energy Source	Hazard(s)	Quantity	Likelihood of Occurrence (Without Safety Features)	Severity (Without Safety Features)	Possible Preventive/ Protective/ Mitigative Measures	Likelihood of Occurrence (With Safety Features)	Severity (With Safety Features)	Risk Level (Without Safety Features/ With Safety Features) Comments
FQL-6	Solvents	Room fire	Assume many liter- to gallon-sized bottles in storage cabinets	Occasional	Critical: Room fire that damages equipment, life-threatening worker injury from burns and toxic smoke exposure (from corrosives in fire)	Nonflammable storage cabinets, flammable-gas monitors	Impossible	Negligible: Exposed flammable materials would be insufficient to engulf the entire room, minimal equipment damage, minor worker injury	High Risk / Routine Risk
FQL-7	Hydrogen gas leak	Hydrogen gas could accumulate in a confined area, build up to a flammable gas concentration, and deflagrate	The quantity of hydrogen that can be discharged from a 0.25-inch-OD, 0.109-inch-ID pipe at choke flow	Reasonably Probable	Catastrophic: The hydrogen could accumulate in an enclosed space and deflagrate, with debris injuring nearby workers	A minimum of six air exchanges per hour in all areas where hydrogen accumulates, interlocked flammable-gas detectors, IR/UV detectors, excess-flow valves	Extremely Remote	Catastrophic: The hydrogen could accumulate in an enclosed space and deflagrate, with debris injuring nearby workers	High Risk / Low Risk Comment: when design details are finalized, it may be possible to show that this event is not Reasonably Probable and lower consequences

Event Scenarios[a]

Scenario Number	Laboratory/ Energy Source	Hazard(s)	Quantity	Likelihood of Occurrence (Without Safety Features)	Severity (Without Safety Features)	Possible Preventive/ Protective/ Mitigative Measures	Likelihood of Occurrence (With Safety Features)	Severity (With Safety Features)	Risk Level (Without Safety Features/ With Safety Features) Comments
FGL-8	Hydrogen pipe deflagration	If a hydrogen air mixture were present in a pipe having a diameter of greater than 1 inch, flame fronts accelerate in pipe and detonate at an L/D of about 10	Explosive gas concentration of hydrogen in a pipe	Occasional	Catastrophic: Near the point of the deflagration, serious worker injuries could occur	Quick-acting flow shutoff valves when rapid discharge is detected	Extremely Remote	Critical: Near the point of the deflagration, serious worker injuries could occur	High Risk / Low Risk
Secure Data Center									
SDC-1	Standard laboratory hazards								

a. The information associated with each event scenario is sometimes incomplete. In those cases, the notation “AI” is used to identify action items. These items, when addressed, would enable the scenario to be better defined, with the result that the risk level could be assigned with greater accuracy.